PIEZOELECTRIC ENERGY FOR SOLDIER SYSTEMS

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ABSTRACT

Piezoelectric materials can be used to convert oscillatory mechanical energy into electrical energy. This technology, together with innovative mechanical coupling designs, can form the basis for an energy harvesting solution for military and commercial systems. The US Army-CERDEC at Ft. Belvoir, VA and Continuum Photonics, Inc. in Billerica, MA completed a three year Science & Technology Objective (STO) research effort that focused on harvesting energy from physical exertion. The effort was aimed at investigating the concept of Piezoelectric Energy Harvesting for supplying supplemental power for dismounted soldiers. This STO effort resulted in the development of four proof-of-concept Heel Strike Units where each unit is essentially a small electric generator that utilizes piezoelectric elements to convert mechanical motion into electrical power in the form factor of the heel of a soldier's combat boot. The Power Technology Branch has tested and evaluated the Heel Strike units. The results of the testing and evaluation and the performance of this small electric generator are presented. The generator's piezoelectric conversion of mechanical motion into electrical power, its efficiency, the processes it goes through to produce useable power and commercial applications of the Heel Strike electric generator are discussed.

1. INTRODUCTION

The US Army Communications Electronics Research Development & Engineering Center (CERDEC) at Ft. Belvoir, VA and Continuum Photonics, Inc. in Billerica, MA completed a three-year Science & Technology Objective (STO) research effort that focused on harvesting energy from physical exertion. The effort was aimed at investigating the concept of Piezoelectric Energy Harvesting for supplying supplemental power for dismounted soldiers. This research effort resulted in the development of four proof-of-concept Heel Strike generators where each utilizes four piezoelectric elements (each one being a Lead Zirconate Titanate (PZT-5A) Bimorph Crystal Stack) to convert mechanical motion into electrical power in the form factor of the heel of a combat boot, where as the user walks, electrical power is generated. The goal of this research effort was to generate 0.5W of power per step and maximize the efficiency by converting most of the mechanical energy into electrical energy. The Heel Strike Generator relies on the piezoelectric effect to generate electric power. Piezoelectricity is the ability of some crystals to generate an electric potential in response to an applied mechanical stress.

When the crystal is under mechanical stress (e.g. by compression or expansion), the electrical charge of the dipoles become aligned, leading to a net electric polarization. This is responsible for the electric potential across the crystal and provides a convenient transducer effect between electrical and mechanical oscillations. If mechanical vibrations are applied to such crystals, they will respond with an electrical oscillation output which can provide power.

This STO program was implemented by the Army because piezoelectric energy harvesting can potentially be a source of energy for some soldier applications such as global positioning systems, dead reckoning systems and the Army survival radio. Piezoelectric heel strike energy harvesting can also be used to power some consumer electronic devices directly such as cellular phones, two-way communicators, and pagers. A useful benefit of implementing energy harvesting would be through battery charging while walking, where energy harvesting can reduce the number of batteries consumed.

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Fig 1: Proof of Concept Heel Strike Generator [2]

2. DESCRIPTION OF HEEL STRIKE SYSTEM

The Heel Strike system consists of two major pieces – the Heel Strike Generator and the power electronics circuit. The Heel Strike Generator is the device shown in Figure 1, where it has a mass of 0.455 kg and has approximate dimensions of 8.89 cm (L) by 7.94 cm (W) by 4.29 cm (H). The power electronics circuit is 5.2 cm square with a height of 1.7 cm and has a mass of 10g. Its purpose is to convert unusable voltage from the Heel Strike Generator to useable voltage (see Figure 3). The power electronics circuit is connected to the Heel Strike Generator to form the Heel Strike System.

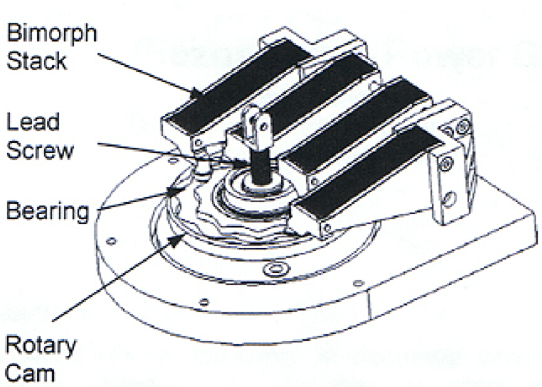

Fig 2: Schematic of Heel Strike Generator [2]

3. PRINCIPLE OF OPERATION

The Heel Strike Generator uses Lead Zirconate Titanate (PZT-5A) piezoelectric materials to transform mechanical energy into electrical energy. PZT-5A was chosen because it has an adequate coupling coefficient and low dissipation, which allow for increased mechanical to electrical efficiency. The input mechanical energy is transformed into electrical energy through four PZT-5A bimorph stacks. Hence the Heel Strike Generator has four phases of electrical energy generation. The Heel Strike System uses a power electronics circuit to extract, store and regulate the electrical energy output from the four phases and converts it into a 12VDC pulse.

When a user steps down and compresses the Heel Strike Generator, a lead screw and gear train convert the linear motion into the rotation of a cam, where the rotating cam causes the PZT-5A bimorph stacks to deflect sinusoidally (see Figure 4). Full compression of the Heel Strike was measured to be 1.0 cm. The stacks are arranged in such a way that they oscillate nearly 90 degrees out of phase leading to a near cancellation of the torques on the rotating cam (see Figure 5). This increases the system efficiency by recycling some of the elastic energy stored in the bimorph crystal stacks [1] (see Figure 5). Each PZT-5A bimorph crystal stack produces an AC voltage (under vibration) that is rectified and regulated by a power electronics circuit that is separate from and connected to the Heel Strike Generator. The power electronics circuit takes in the AC voltage from each phase of the Heel Strike Generator, rectifies them and produces DC pulses that charge a storage capacitor. Any stored charge in the capacitor is then discharged through a DC-DC converter, which converts that stored energy into a regulated 12VDC output pulse (see Figure 4).

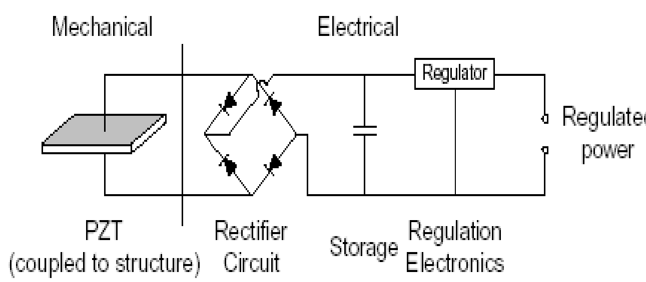

Fig 3: Schematic of Heel Strike operation

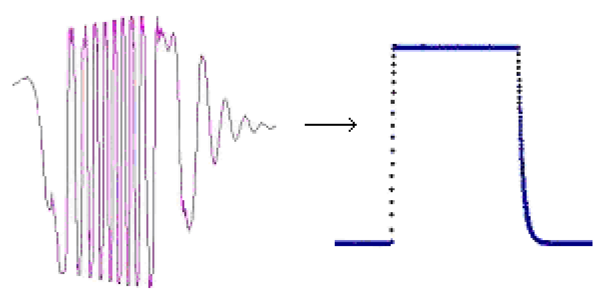

Fig 4: Typical output DC pulse that was rectified from the AC voltage signal

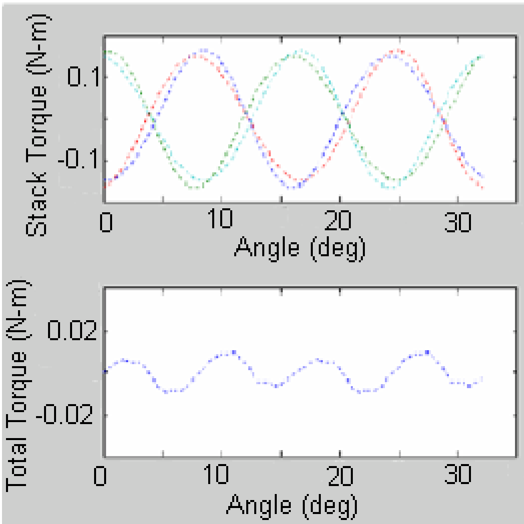

Fig 5: Torques on the cam from the bimorph stacks. Total torque is nearly cancelled.

4. TEST AND EVALUATION

The electrical performance of the Heel Strike System was tested at ambient conditions where the temperature was approximately 297 K and the pressure was approximately 1 atm. The purpose for testing the Heel Strike System was to determine its power output under full and partial compression, and to determine if the power output is adequate for commercial and military applications. The Heel Strike Generator was tested at various compressions (25% of full compression, 50% of full compression and 75% of full compression). The 100% full compression (1.0 cm) was avoided due to the fact that one of the Heel Strike Generators had failed while operating at this compression. The purpose of testing the Heel Strike to varying compressions is to take into account the human factors involving weight since not every user weighs the same. i.e., a heavy person will likely compress the Heel Strike Generator more than a light person as he/she steps on it.

During this test, each phase of the Heel Strike Generator was connected to the power electronics circuit. The Heel Strike Generator and the power electronics comprise the Heel Strike System. The Heel Strike System was connected to a variable resistor as shown in Figure 6. The connection was made such that power was delivered from each phase of the Heel Strike Generator to the power electronics circuit and finally dissipated in the variable resistor. The Heel Strike Generator was compressed by a cam that was attached to a shaft of a motor. The motor would turn the shaft such that one compression per second would result on the Heel Strike due to the cam striking it. Various cam sizes were used to complete the desired compressions of 25%, 50% and 75% of the full compression.

Resistive loads of 1 to 200 Ohms were applied to the Heel Strike System under compressions of 75%, 50% and 25% respectively. At each resistive load and compression the electrical voltage, current and time duration of the output DC pulse was measured using a Data Acquisition (DAQ) System. The voltage and pulse time duration was measured by counting the number of divisions on the DAQ scope and multiplying by an appropriate conversion factor. The current was measured using a 5A-50mV shunt resistor, counting the number of divisions and multiplying by an appropriate conversion factor. The power of the output DC pulse was computed by multiplying the voltage, current and pulse time duration (since we are assuming one step per second and power is in joules per second). That is:

$$Power = \frac{EnergyDelivered}{Second} = \frac{IVT}{1s} \qquad (1)$$

Where I is the electrical current, V is the electrical voltage and T is the pulse time duration. Power was measured at each compression and plotted versus resistance (see Figure 7).

5. TEST AND EVALUATION RESULTS

The results of the test are displayed in Figure 7 which show the power output (energy delivered per second) of the Heel Strike System at each compression and electrical resistance. Based on the power data measured, the power output of the Heel Strike System appears to be steady and independent of stroke compression and external resistance.

On average the Heel Strike System produced 0.0903 watts of Power per strike with a standard deviation of 0.0059. All data points in Figure 7 were used to compute the average and standard deviation of power. Table 1 suggests that the Heel Strike System could provide power to some communication devices in either the stand-by or active mode. Some procedures are suggested to improve the Power output in section 7.0.

The efficiency of the Heel Strike System may be approximated by calculating the gravitational energy that is released through 1.0 cm (full compression) and dividing that by the average energy produced by the Heel Strike System in one step. The gravitational energy is computed as:

$$U = Mgh \qquad (2)$$

Where M is the mass of the person stepping on the Heel Strike, g is the acceleration due to gravity (9.80 m-s^{-2}) and h is the full compression of the Heel Strike (1.0 cm).

For the age category of 20-74 the average mass of an adult male is 86.71 kg, and the average mass of an adult female is 74.59 kg [3]. These masses can further be averaged into 80.65 kg. Therefore the average gravitational energy released by an adult person stepping down 1.0 cm is 7.90J = 80.65 kg × 9.80 m-s^{-2} × 0.01 m. The efficiency of the Heel Strike system is thus approximated as 0.09/7.90 ≈ 0.01 = 1%.

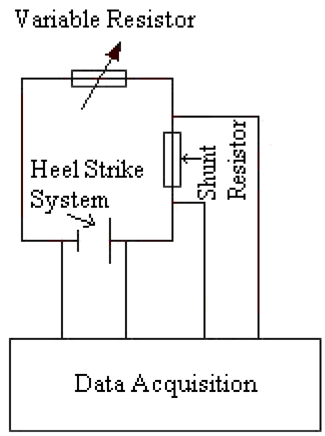

Fig 6: Diagram of Test Stand [2]

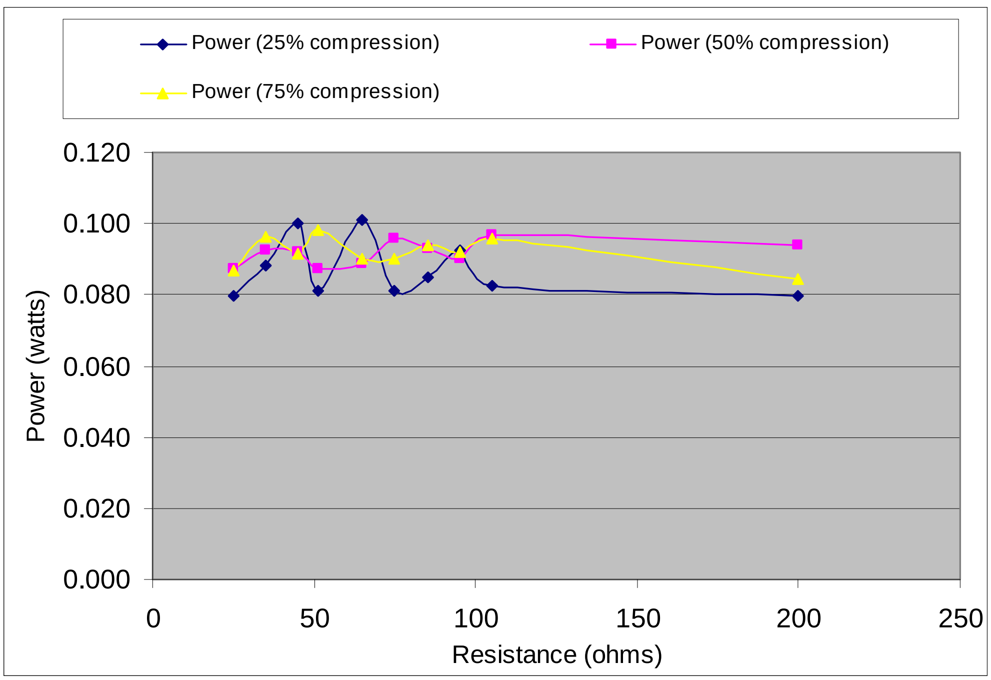

Fig 7: Output DC Pulse Power at compressions of 25%, 50% and 75% [2]

Table 1: Power Consumption of various commercial Communicators [2]

Products	**Battery Voltage (volts)**	**Power Consumption in Stand-By Mode (watts)**	**Power Consumption in Active Mode (watts)**
Cellular Phone	Lithium ion battery (3.6V)	0.042	1.7
Two Way Communicator	3-AA batteries (4.5V)	0.158	0.675
Pagers	1-AA batteries (1.5V)	0.023	0.030

6. CONCLUSION

The average power produced by the Heel Strike System is much less than the target of 0.5 watts. This might be attributable to several issues that were found in the development of the Heel Strike. It was found in the later stage of development that the mechanical forces resulting from the oscillation of the bimorph crystal stacks were not completely canceled, and as a result an opposing toque from the unbalanced bimorph forces was applied to the cam. This leads to a force opposing the input to the Heel Strike Generator so as the user steps down, there is some resistance and not all of the downward force would be used to oscillate the bimorph stacks. This results in lower mechanical to electric efficiency. There are two primary causes for the bimorph forces not completely canceling. One is the stiffness variations in the bimorph stack assemblies and the other is due to the location of the bimorph crystal stack assemblies relative to each other. The variations in the stiffness of the bimorph stack assemblies can cause the mechanical load to be unbalanced because the variations occur in stacks that are phased to nearly cancel each other. The locations of the bimorph stacks have to be tuned and controlled properly for the bimorph forces to completely cancel. These issues should be addressed to determine if the power output can be increased to the target level of 0.5 watts. If the power output can be increased to the target level by addressing some or all of these issues, further Testing of the Heel Strike System is recommended.

7. FUTURE OF RESEARCH AND DEVELOPMENT ON PIEZOELECTRIC HARVESTING

There are many possible improvements that can be implemented for the Heel Strike Generator. Two methods of improvement would be to use bimorph materials with lower stiffness and to maintain the uniformity of the stiffness across all four bimorph crystal stacks. Reducing the bimorph stiffness and the use of an additional gear system can have a large impact in providing higher output power since the number of blade deflections can be increased.

A lesser bimorph stiffness would also result in less resistance as one presses down on the Heel Strike Generator. A more uniform stiffness across all four bimorph stacks will result in more cancellation of the bimorph forces leading to increased bimorph blade deflections per strike and thus increased mechanical to electric efficiency, and increased DC power output. One way to reduce the bimorph stiffness would be to change the central shim material that the piezoelectric ceramic pieces bond to.

This material currently is stainless steel. However using a fiberglass, plastic, or aluminum shim may reduce the blade stiffness. Other materials such as single crystal piezoelectrics may reduce stiffness.

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